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A Conceptual Design for an Imploding-Liner Fusion Reactor (Linus)

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Plasma Physics Division

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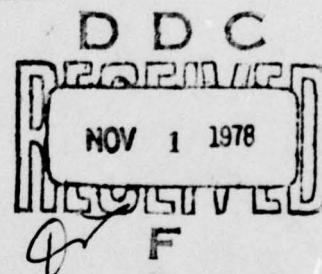
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the conceptual design of a fusion reactor based on the dynamic compression of a magnetically-confined DT plasma by an imploding liquid lead-lithium liner. Stable implosion-expansion cycles are achieved by rotating the liner, and imploding it by a means of a rigid mechanism driven by high pressure helium (the 'captive liner' principle). At peak compression the magnetic field is 0.5 MG and the liner is 1 m thick, which is enough to absorb the fusion neutrons. The energy of the trapped α-particles is directly
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recovered in the expansion and compensates for the resistive and mechanical losses in the liner, making the mechanical cycle self-sustaining. The reactor works rather like an internal combustion engine, except that there is no shaft output: all the nuclear energy appears in the liner as heat. The initial plasma is created by means of a pulsed rotating relativistic electron beam injected from one end. The beam sets up both the plasma and the confining magnetic field, and no external magnet coils are required. The reactor is repetitively cycled at 1.67 Hz for a gross electrical power output of 1000 MW.

This concept leads to a rather simple fusion reactor because of the many functions performed by the liner. It serves as the main confining coil, the tritium breeding blanket, and the heat transfer medium; it heats the plasma by direct mechanical compression, and the inside surface is a 'first wall' which is reformed after each cycle. This last feature allows the mean wall loading and the engineering power density to be 3-5 times greater than in a steady state Tokamak reactor.

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A CONCEPTUAL DESIGN FOR AN

IMPLODING-LINER FUSION REACTOR (LINUS)

I.   Introduction

The major effort in fusion research throughout the world is being
devoted to the tokamak approach,[1] which is certainly closest to
achieving the physical conditions needed for a controlled fusion
reaction. In the past few years there has been a growing realization
that, although the tokamak may be the first to reach the technical
objective of producing net electrical power, it may prove difficult to
develop it into a commercial power source owing to its rather low power
density, its complex construction and its highly sophisticated tech-
nology. These concerns have led to a renewed interest in alternative
approaches which, although at present less highly developed than the
tokamak, might ultimately lead to a simpler and more economical fusion
reactor.

A fusion concept known as Linus has been under development at NRL
since 1972.[2,3,4] This approach utilizes the principle of plasma
compression by imploding liners pioneered by Linhart[5] at Frascati and
Alikhanov[6] in the USSR, except that in the course of its evolution the
Linus concept has moved away from the extremes of plasma pressure
proposed by those workers and is now based upon a non-destructive,

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reversible compression-expansion cycle produced by simple mechanical means.[9],[10] The Linus reactor is best described as a fusion engine, and is unique among magnetic confinement schemes in that it has moving parts, a continuously regenerated liquid 'first wall', and no external magnet coils. The mean wall loading and the engineering power density are both 3-5 times greater than in a tokamak, resulting in a significantly smaller reactor for the same power.

The Electric Power Research Institute has recently initiated a study of alternative fusion concepts, in which the proponents of each concept are required to submit a design for a 1000 MW(e) reactor. These reactor designs will be incorporated into conceptual power plant designs by the Bechtel Corporation, who will provide details of the balance of plant, and make overall cost estimates. This study should allow a comparative evaluation to be made of the alternative concepts, both in relation to each other and to the tokamak approach. In view of the relatively undeveloped state of most alternative concepts, it is also likely to indicate those areas where further development is needed before any final judgment can be made.

This report describes the Linus reactor design prepared for the EPRI study.

II. General Principles

The principle of the Linus reactor is to compress a magnetically confined plasma to high density and fusion temperature by means of an imploding, rotating cylinder of liquid metal, known as a liner.[7],[8],[9],[10] The compression is dynamic, that is to say, kinetic energy is

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accumulated by the liner from a driving source over the relatively long period of the implosion, and delivered to the compressed field-and-plasma payload in the much shorter period during which the liner is brought to rest. In the reactor to be described here the driving source is a reservoir of high-pressure gas. Using large but attainable driving pressures (2000-4000 psi) the peak confining magnetic field is in the range 0.5-0.7 megagauss, and the corresponding plasma density at fusion temperature is a few times $10^{17} cm^{-3}$. The containment time required for net fusion yield is then relatively short (a few hundred microseconds).

The sequence of events that makes up one cycle of reactor operation is shown in Fig. 1. The rotating liner is set up inside a stationary cylindrical vessel and compressed gas (helium) is contained in a number of adjacent storage tanks (Fig. 1a). To initiate the implosion, valves open to admit gas to the vessel, thus applying pressure to the outside of the liner. Shortly after the liner has begun to move (Fig. 1b) the initial plasma and its associated confining magnetic field are set up inside the liner by a method which will be described later. The liner comes to rest on the dense plasma, which has been raised to fusion temperature by adiabatic compression (Fig. 1c). The nuclear reaction rate is sharply peaked around maximum compression, at which time the liner is thick enough to absorb the fusion neutrons. The compressed state is maintained for a limited time (the dwell time) by the inertia of the liner, after which the plasma and liner expand. The α-particles from the reaction are trapped in the plasma, increasing its pressure and adding to the energy of expansion (Fig. 1d). The expanding liner

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pushes the driving gas back into the storage tanks and the valves close until the next cycle (Fig. 1a). The system is designed so that the α-particle energy <u>exactly</u> compensates for the mechanical and electrical losses in the liner, making the implosion-expansion cycle mechanically self-sustaining. The reactor thus behaves rather like a reciprocating internal combustion engine, except that there is no shaft output; all the nuclear energy appears in the liner as heat.

Because the energy of the expanding liner is efficiently returned to the driving source, the Q of the reactor is much lower than in fusion systems where the energy is recovered via a thermal cycle. Here Q is defined as the fusion energy release integrated over one cycle divided by the mechanical work done in imploding the liner. It is a feature of all liner systems that, other things being equal, Q is proportional to the radius, and the energy per unit length is proportional to Q^2. The low Q (typically ~ 2) of a Linus reactor is an important factor in keeping the dimensions of the system and the energy storage requirements within acceptable limits.

Compared with the Los Alamos fast liner concept,[11] in which a solid liner is imploded at $\sim 10^6$ cm.sec^{-1} and is destroyed at each shot, the liner in a Linus reactor is rather slow ($10^3 \sim 10^4$ cm.sec^{-1}). This is the inevitable consequence of requiring the cycle to be reversible and non-destructive, and it puts severe requirements on the containment of the plasma at the ends. A confinement system with closed magnetic field lines is necessary, and the configuration chosen for the Linus reactor is a highly elongated toroidal belt-pinch, with both poloidal and toroidal field components (Fig. 2). The configuration

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is set up inside the liner by means of a pulsed rotating relativistic electron beam injected from one end.

The principal attraction of the Linus concept is that it leads to a rather simple fusion reactor because the liner performs a number of functions which in other reactors require separate systems. It is the main confining coil, the tritium breeding blanket, and the heat transfer medium; it provides the majority of the plasma heating energy by direct mechanical compression, and the inside surface is a 'first wall' which is reformed after each cycle. Although the plasma is magnetically confined, there are no external magnet coils. The magnetic configuration is set up inside the liner by the electron beam, and the implosion-expansion cycle takes place in a time short compared with the penetration of the magnetic field into the liner. The elimination of magnet coils is an obvious simplification and economy, but probably the most important consequence of keeping all magnetic fields inside the liner is that the reactor may be built of ferritic steel.

To realize the potential of the Linus concept, development is needed in three main technological areas: the manipulation and implosion of the liner, the formation and confinement of the plasma, and the removal of heat from the reactor. None of these areas appears to contain insuperable obstacles to the development of a reactor.

III. The Liner

In order to achieve the efficient, direct energy recovery that is a central feature of the concept, it is essential that the liner motion should be stable throughout the entire compression-expansion cycle.

This is achieved by making it of liquid metal, and constraining it in a rigid rotating structure. This arrangement is known as the captive liquid liner.[7] It has been shown theoretically[12] and demonstrated experimentally,[9,13] that if the liner has sufficient angular momentum the inner surface is stable to the Rayleigh-Taylor instability, which would otherwise destroy it at turnaround. A consequence of the stability criterion is that the energy in rotation at turnaround is about equal to the energy in the compressed plasma. Owing to the conservation of angular momentum this rotational energy is drawn from the liner driving source, and the initial rotation required is quite modest.

The outer surface cannot be stabilized by rotation, and must be mechanically constrained. Some experiments in which the liner is driven by pistons have been performed on small-scale models,[9,14] but none of the arrangements used so far is suitable for a reactor, for which the important requirements are that the diameter of the rotating mechanism should be kept to a minimum, and that there should be free circulation of the liner material to facilitate heat removal. A new mechanism which satisfies these requirements is shown in Fig. 3. A quasi-cylindrical shell is made up of a number (in this case 12) of long, angled beams which form a polygon whose sides can change length as the beams slide over each other, thereby changing the diameter of the shell. The sliding surfaces are maintained parallel by guide fingers, and the ap   of each beam is maintained parallel to a line on the circumference of a rigid rotating cylinder by a number of evenly-spaced connecting rods (Fig. 4). This arrangement ensures that the

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axis of the shell remains coincident with the axis of rotation as the shell collapses.

The structure rotates inside a stationary pressure vessel. Initially (Figure 3a) the shell is at its outermost radial position and the liquid metal occupies a relatively thin annulus. The rotational speed is sufficient to provide a smooth inner surface, and to ensure stability of the surface at turnaround. To initiate an implosion cycle, valves spaced round the periphery admit high pressure gas from storage reservoirs into the pressure vessel, driving the shell and the liquid metal radially inward to compress the plasma and its associated magnetic confining field (Fig. 3b). After turnaround, the process reverses and energy returns via kinetic energy of the pistons and liner to the internal energy of the gas in the reservoirs; when the shell reaches its outermost position, the valves close until the next cycle. The liquid metal is circulated through the system in the axial direction to remove the heat.

The main body of the liner consists of a mixture of lead and lithium, with probably a small percentage of other metals. Some preliminary studies by Dudziak[28] have shown that a 1 m thick liner of 50% PbLi, 42% Pb and 8% Cd would give a tritium breeding ratio of 1.15 and absorb 92% of the neutrons. This work established the basic effectiveness of a lead-lithium liner, although further studies are needed to determine the optimum composition. The (n, 2n) reactions in lead provide a surplus of neutrons which is almost embarrassing. Although the liner absorbs almost all the neutron energy, there will be a leakage flux which may require more shielding than provided by the

liner mechanism. Lead appears to be the best liner material on account

of its high density and low compressibility which leads to high peak

pressures and long dwell times (the lithium being added only to absorb

the neutrons and breed tritium). On the other hand lead is a poor

electrical conductor and a highly undesirable plasma contaminant. It

therefore seems necessary that the inside surface of the liner should

consist of pure lithium, both to minimize the resistive penetration

of the magnetic field and to reduce plasma contamination. This

stratification of the liner leads to the complication of two liquid

circuits through the reactor, although this arrangement has advantages

for heat removal, as will be discussed later.

IV. The Plasma

Creating a magnetically confined plasma inside the liner is a

non-trivial problem. The method chosen is to use a pulsed rotating

relativistic electron beam injected from one end. The rotating beam

is created by a special annular diode which incorporates an iron-cored

magnet to produce a radial magnetic field in front of the anode (Fig.

5). The interaction of the axial velocity component of the beam with

the radial field gives the beam its azimuthal velocity component. The

beam is injected parallel to the axis into neutral gas contained within

the liner (Fig. 6). Because the total flux within the liner is zero,

the axial magnetic field (B_z) outside the beam is in the opposite

direction to the field on axis. The beam breaks down the gas, heats

the resulting plasma, and passes out of the system. The magnetic field

carried in by the beam is frozen into the plasma on account of the

conductivity produced by the beam heating. The conducting end walls
ensure that the B_z field lines close round the ends of the plasma.
The plasma also contains the frozen-in B_θ field of the beam; the
ratio B_z/B_θ is determined by the pitch of the beam, which in turn
is controlled by the field in the diode. Unlike the earlier Astron
concept,[15] in which the beam electrons themselves create the confining
field, the beam passes through the system and leaves behind a reversed
magnetic field configuration sustained by plasma currents alone. Note
that the beam produces both the plasma and the magnetic field required
to confine it; no externally-applied magnetic field is necessary. The
plasma pressure is supported by the field of the currents that are
induced on the inside surface of the liner in order to conserve the
flux within it.

The process described here is a very effective way of conveying
magnetic energy into a closed conducting cylinder and has been
demonstrated in a number of experiments.[16,17,18] The efficiency of
creation of magnetic energy from beam energy can be as high as 50%.[19]
The heating of the plasma during the passage of the beam however is
quite small (~ 10 eV) and to reach the temperature of several hundred
eV necessary as a starting point for adiabatic compression to fusion
temperatures, further heating of the initial plasma is necessary. If
the beam produces an annular plasma which is very thin compared with
the radius of the liner, this will happen spontaneously. The
configuration will contract to reduce its magnetic energy, in the way
that a solenoidal coil moves to increase its inductance. The
contraction will generate axial shock waves which will convert magnetic

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energy into plasma thermal energy, as has been observed in certain theta-pinch experiments.[20] The contraction will stop when axial pressure balance is achieved. Compression by the liner will result in elongation of the plasma, so that at peak compression the plasma will once again occupy the full length of the system (Fig. 7). Note that the proximity of the liner to the plasma boundary at all times is a favorable condition for plasma stability.

The highly elongated toroidal configuration described here is very similar to the Garching belt-pinch,[21,22,23] which has demonstrated stable confinement of plasma at $<\beta> = 0.6$ for a time apparently limited only by classical transport and radiation.[24] Similar, although not identical configurations have already been set up with rotating electron beams.[16,17] Numerical studies[25] of particle and energy transport including classical and anomalous effects predict that, on the scale of a reactor, the losses from the plasma in the belt-pinch configuration will be insignificant during the compression-expansion cycle.

V.   Heat Removal

Heat is deposited in the liner from two sources: the energy of the fusion neutrons, which is absorbed in the main body of the liner, and the resistive dissipation of the induced skin currents, which heats the inner layer. This resistive dissipation is the principal source of inefficiency in the implosion-expansion cycle and, as has been previously described, to make the cycle mechanically self-sustaining the lost energy must be replaced by the energy of the α-particles, directly recovered in the expansion. The α-particle energy thus appears

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as heat in the skin layer of the liner. For each fusion reaction the neutron carries 14.1 MeV and releases a further 4.8 MeV upon capture in the liner. The α-particle carries 3.5 MeV, accounting for 15.6% of the total nuclear energy.

The imploding liner surface experiences a magnetic pulse which raises the lithium temperature by $\Delta T \simeq 4000B^2$ where B is the peak magnetic field in MG. Thus if the initial temperature is 315° C a field of 0.5 MG will raise the surface temperature to $\sim 1315^\circ$ C, which is the normal boiling point of lithium. The lithium surface must therefore be swept out of the reactor after each cycle. To avoid an excessive temperature at the outlet of the reactor the surface must be mixed as it leaves with a cooler lithium layer of sufficient depth that the outlet temperature is no greater than 500° C. This layer then carries 16% of the reactor's heat output; the remaining 84% is absorbed in a much larger volume of lead-lithium, which is circulated through the reactor more slowly, the replacement time corresponding, typically, to ~ 3 cycles. The heat removal is thus best accomplished by having two circuits through the reactor, a 'fast' circuit of pure lithium and a 'slow' circuit of lead-lithium alloy. The fast circuit has the added function of introducing a cool lithium surface which condenses the lithium vapor that fills the chamber after each cyle. The vapor pressure of lithium at an inlet temperature of 315° C is 10^{-8} Torr.

While in the reactor, the liquid metal needs to have a rotational velocity of ~ 15 m.sec^{-1} in order to satisfy the criterion for rotational stabilization. This is 3-4 times faster than its velocity

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in the inlet and outlet pipes; the rotational energy is given to the
liquid on entry by a radial-flow pump, and recovered by a turbine upon
leaving (Fig. 8). The pump and the turbine are coupled together through
the rotor, so that the driving motor has only to supply the net power
needed to circulate the liquid through the reactor and the external
heat exchangers.

VI.   The Reactor Working Point

The working point of the reactor is determined principally by the
requirement that the mechanical cycle should be self-sustaining. The
variables necessary and sufficient to define the system are:

ρ, c, η the density, sound speed and resistivity of liner material.

R   the initial inside radius of the liner.

α the compression ratio R/r_o, where r_o is the compressed

radius.

p   the driving pressure.

$<\beta^2>$ the average of β^2 in the plasma at peak compression.

The basic scaling law for Q_p, the ratio of nuclear energy to
plasma energy is

$$Q_p = Rp^{\frac{1}{2}} \rho^{\frac{1}{2}} < \beta^2 > F(\alpha, p/\rho c^2) \tag{1}$$

In Fig. 9 the function F is plotted against α with $p/\rho c^2$ as
the parameter. It has a pronounced maximum for $\alpha \sim 10 - 12$, whose
value is rather insensitive to $p/\rho c^2$. Higher compression ratios lead
to reduced Q_p on account of compressibility effects in the liner.
The value of $<\beta^2>$ also decreases as α increases.[27]

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The condition for a self-sustaining cycle is

$$0.156 \ Q_p \geq f_\eta \qquad (2)$$

where f_η is the ratio of the resistive energy loss to the plasma energy. Other things being equal, f_η scales as

$$f_\eta \propto \eta^{\frac{1}{2}} R^{-\frac{1}{2}} \qquad (3)$$

where η is the resistivity of the liner. Note that in choosing η the heating of the liner by the magnetic pulse must be taken into account (non-linear magnetic diffusion[30]).

Clearly (2) can always be satisfied if R is greater than some value R_m. The problem facing the reactor designer is to find values for the system parameters that will minimize R_m, since a factor of two in this quantity can make all the difference between an attractively compact reactor and an engineering monstrosity. For the purpose of this study, a reactor design code based on a simple model[26],[27] which includes all the variables listed above has been used to determine a range of working points. In general, R_m decreases as p is increased. For the reference design a driving pressure of 2400 psi was chosen on the somewhat arbitrary grounds that this leads to a thickness of 20 cm for the steel walls of the helium reservoirs. The main parameters of the reference design are given in Table 1. The sensitivity of the working point to the choice of driving pressure will be discussed later.

The trajectory (radius vs. time) of the inside surface of the liner is shown in Fig. 10. The mean implosion velocity is

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4.5×10^3 cm.sec^{-1}. The plasma is injected when the liner velocity

reaches 500 cm.sec^{-1}. The plasma heating by adiabatic compression

then exceeds plasma losses by thermal conduction, and the magnetic

Reynolds number, $4\pi Rv/\eta$, is about 15, indicating that magnetic flux is

being compressed by the liner. This velocity is reached before the

liner has covered 1% of its travel, so the liner compression ratio

and plasma compression ratio can be taken as identical.

VII. The Reactor

Fig. 11 shows a layout of the reactor, and Figs. 12 and 13 show

cross-sections at selected points. The initial inside diameter of the

liner is 3.2 m; the outside diameter of the rotor is 4.9 m. The rotor

is 12.9 m long and is constructed on the principles shown in Fig. 3.

In this embodiment however, the valves are incorporated in the rotor

itself, which rotates inside a permanently pressurized vessel which

constitutes the main frame of the reactor. The latter is directly

connected to eight cylindrical reservoirs placed symmetrically round

the main frame which store a total of 485 m^3 of pressurized helium.

The valve mechanism is shown in Fig. 14. The valves are attached to

the connecting rods and are held in the closed position by the

centrifugal pressure of the liner, amplified by the mechanism. To

initiate an implosion, pilot valves admit high pressure to the back of

the solid shell, lifting the main valves off their seats and admitting

the driving gas from the reservoirs. When the liner returns to its

original position the main valves are automatically closed. A suction

line removes excess pressure from the back of the shell, which then

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remains in its outermost position until the next cycle.

The rotor is supported by liquid metal hydrostatic bearings,*
evenly spaced along its length, and is rotated at 100 rpm by a 72-pole,
wound-rotor induction motor of 10,000 horsepower. The liquid metal
inlet manifold is at the driving end, and contains two concentrically
mounted pumps for the two liquid metal circuits. At the outlet end
there are two corresponding turbines which extract the rotational
energy before the liquid metal leaves the reactor. The rotor forms
the shaft connecting the pump impellers and the turbine runners; the
torque reaction on the fixed blades is taken by the main frame. The
pumps are larger than their associated turbines, to make up for the
internal pumping losses and to provide additional pumping power for
circulating the liquid metal through the externally-mounted inter-
mediate heat exchangers. The reactor is thus its own circulating
pump. The axial flow through the reactor is interrupted momentarily
by the implosion. Surge tanks are incorporated in the inlet end to
maintain continuity of flow in the external circuit; these tanks are
situated inside the ends of the rotor and the restoring action is
provided by centrifugal force.

Each end of the rotor is closed by a massive steel plug which is
free to recoil on splines against a number of hydraulic recuperators.
These plugs take the shock load imparted to the ends by the pressure
of the imploding liner, and reduce it to an acceptable level before

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* Other bearing options may emerge from further studies.

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communicating it to the frame of the reactor. The electron beam used
to create the initial plasma is injected through a long annular slit in
one end plug. The conductance of the slit is low enough to allow a
satisfactory pressure differential to be maintained between the electron
beam generator and the reactor chamber by two large vertical-axis
turbomolecular pumps mounted on the generator. For structural reasons
the annular gap is bridged by a number of radial spokes, which are
contoured to match the pitch of the rotating beam. The entrance to the
reaction chamber is equipped with a mechanical shutter which is operated
at the same time as the liner implosion mechanism (Fig. 15). This shutter
closes the annular slit during implosion to prevent liquid metal from
entering the generator.

Assuming that the plasma is created by the beam with 50% efficiency,
the necessary beam energy is 22 MJ per pulse. Typical parameters might
be 1.5 MA at 3 MV for 5 μsec. A beam generator of this size using
existing Marx generator technology would be physically larger than that
shown in Figure 11. However, it is most likely that by the time this
reactor is built, inductive energy storage technology will have been
developed to the point where it can be applied to the generation of
electron beams of this size. For the moment therefore, the generator
in Figure 11 should be regarded as schematic.

The fueling of the reactor is accomplished by injecting a charge
of D-T from injectors in the end plugs just before firing the electron
beam generator. The injectors produce supersonic jets which are
directed so as to avoid the fresh liquid surface of the liner. After
the pulse the residual plasma is lost to the wall and the D-T combines

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chemically with the lithium. The fresh stream of cold lithium condenses the lithium vapor and evacuates the chamber in readiness for the next pulse. The small quantity of helium 'ash' is either occluded in the lithium or pumped out through the electron injection slit.

VIII. Thermal Conversion System

The liquid metal from the reactor is circulated through intermediate heat exchangers inside the containment building, transferring the heat to non-radioactive sodium circuits and thence to steam generators. This arrangement is similar to that used in the LMFBR. Although the need for an intermediate loop for a fusion reactor is debatable, it will probably be a requirement for licensing, and so is included in this design.

Temperatures and coolant flow rates are shown in Fig. 16. A low-temperature saturated steam cycle is proposed, based on the arguments in favor of this system (compared with a super-heated steam cycle) used in the GE-Bechtel PLBR design.[31] In the case of the Linus reactor, it is desirable to keep the reactor temperature low to make the mechanical requirements of the machine (principally the fatigue life) easier to satisfy. The main frame of the reactor and the helium storage reservoirs are kept at the inlet temperature of 313° C (595° F) and so should not experience problems with creep.

IX. Ancillary Systems

The principal ancillary systems are as follows:

(a) A gas extraction system to remove the tritium and unburnt deuterium from the liquid metal.

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(b) A metal processing system to maintain the purity of the lithium in the fast circuit and to maintain the appropriate lead-to-lithium ratio in the slow circuit in the face of the mixing, albeit small, between the circuits inside the reactor.

(c) A pressure makeup system, to return to the reservoirs the small amount of helium that is used by the valve mechanism and is not returned directly at the end of each cycle. This system would also be used to transfer the helium to alternative storage upon shutdown of the reactor.

(d) A liquid metal scavenging circuit to collect the lead-lithium that will, as in all hydraulic systems, leak past the metal-to-metal seals of the mechanism. The lowest helium reservoir will act as a sump for this fluid.

(e) A pressurization and circulation system for the bearings.

The design of any of these systems is beyond the scope of this report.

X. Reactor Startup

When the reactor is shut down, the liquid metal is drained into thermally insulated storage tanks where it is held at just above its melting point by electric heaters. The helium is stored under pressure in separate storage tanks. To start the reactor the following sequence is observed:

(a) The structure of the reactor is brought to its working temperature by electric heaters.

(b) The rotor is brought up to speed.

(c) The liquid metal is pumped into the reactor (this may occur

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simultaneously with (b)).

(d)   The helium is pumped into the reservoirs.

(e)   The reactor is operated until it starts generating steam.
All the above operations require power to be supplied from the grid.
After (e) the reactor generates the power to run itself. The shutdown
procedure would be the same sequence in reverse.

XI. Maintenance

Maintenance of any fusion reactor is complicated by the induced
radioactivity, but in the case of Linus the simplicity of the system
and its linear configuration are mitigating factors.

The most frequent maintenance will be required by the electron
beam generator, which is well shielded by the massive end structure.
The generator can be detached and removed on rails to a maintenance
bay. Next there is the maintenance of the rotor, in particular the
valves, which entails dismantling the reactor with remote-handling
equipment. The procedure is shown in Fig. 17. With the generator
removed, the end plate is slid off on airpads. The railway is used
to bring up a special maintenance vehicle with a cradle to receive
the rotor, which is drawn out of the reactor frame by means of a
hydraulic extractor mounted on the vehicle. Oil is pumped through
the hydrostatic bearings to lift and lubricate the rotor as it is
being extracted. The rotor is then removed to a maintenance bay where
it can be serviced with remote handling equipment.

Because most of the neutron absorption takes place in the liner,
which is pumped out of the reactor before maintenance begins, it is

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likely that the induced radioactivity in the permanent structure will be somewhat less than in other fusion reactor designs. This needs to be confirmed by detailed neutron transport and activation studies, which are beyond the scope of this report.

XII. Scoping Studies and Cost Estimates

The Linus reactor is a large rotating machine constructed of steel to nuclear pressure vessel standards. At the present stage of design only approximate cost estimates are possible on a $/kg basis, and even this is made difficult by the lack of similar machines with which to draw an analogy. The amount of steel in the reactor depends on the scale, the working pressure, and the stress in the steel. In the reference design the steel is taken to be $2\frac{1}{4}$ Cr-1 Mo alloy stressed to 13.5 ksi; this is comparable to the stress in a pressurized-water reactor vessel. The biggest uncertainty lies in the appropriate choice of working stress in a machine that has cyclic as well as constant stresses. In the design described here, the main frame and reservoirs are continuously pressurized, but a pressure drop of 26% occurs during each implosion as the helium expands, resulting in a corresponding drop in the material stress. Fatigue is therefore an important consideration. Rudimentary fracture mechanics calculations, together with information on stresses in large reciprocating engines, indicate that the above level is probably acceptable, but far more detailed studies are needed to confirm this. There is some flexibility in the design for reducing the stress levels: for example, the helium reservoirs could be spherical rather than cylindrical. Also

the pressure fluctuations could be reduced by increasing the volume of the helium reservoirs relative to the reactor volume, although it can be seen from Fig. 11 that to greatly exceed the 5:1 ratio of volumes used there would lead to a much more cumbersome machine.

The engineering parameter that has the most impact on the design of the reactor is the working pressure. The reactor design code has been used to generate sets of parameters for reactors with working pressures both above and below the 2400 psi reference level. In each case the ratio of length to diameter is maintained at 4 (which is required for reasons of plasma stability) and the compression ratio α chosen to maximize the function F (Equation 1). The results are given in Table 2.

The comparative weight factor is obtained by assuming that the thickness of all the parts is adjusted to keep the same stress in the steel (using the formula for cylindrical pressure vessels[29]). This approach is overly simple, since not all parts are equally affected by pressure, and is also a little naive, since the thickness of the pressure vessels, which is already 20 cm at 2400 psi, cannot be increased arbitrarily. However, the important result from this exercise is that although increasing the working pressure reduces the physical size of the reactor, the weight is practically unchanged owing to the thicker sections needed. The nuclear energy per cycle is decreased as the pressure is increased, so that an increased repetition rate is needed to maintain the same power output. The energy of the electron beam generator increases with increasing pressure, leading to a greater circulating power fraction. The overall economic equation is obviously a very complicated one, but it seems that the pressure of

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2400 psi chosen for the reference design is not far from optimum.

Weight and cost estimates for the main components of the reference reactor are given in Table 3. Included are estimates for the electron beam generator, made on a $/J basis, and for the induction motor, which is one of the few components for which no development is needed.

Although actual cost estimates at this stage are of questionable value, the results of the present study at least allow a comparison to be made of the engineering power density and total materials requirements for the Linus reactor relative to other fusion reactors and the LMFBR. Table 4 shows this comparison. The numbers for the other systems come from a recent report by Kulcinski,[32] who uses them to illustrate his conclusion that, owing mainly to its lower power density, the average DT fusion system (by which he means a tokamak) is likely to be appreciably more costly than the LMFBR. Table 4 shows that this conclusion does not hold for the Linus reactor which, on the basis of this comparison, has twice the power density of the LMFBR.

XIII. Discussion

This study represents a first attempt at a comprehensive conceptual design of a Linus fusion reactor. This reactor has a number of unique features that allow it to circumvent some of the problems of more conventional fusion concepts. In particular, the liquid metal 'first wall' allows much higher wall loadings than are possible with solid walls. The neutron wall loading in the Linus reference reactor,

referred to the liner in its expanded state, is 17.5 MW.m^{-2},[*] nearly

five times greater than in current Tokamak designs.[33] This in turn

leads to the higher engineering power density which is one of the

principal attractions of the concept.

If a Linus reactor could be developed along the lines suggested

here, it could lead to a power source that would be economically

competitive with the LMFBR. However, as with all 'exploratory' fusion

concepts, this optimism is based on the assumption that the problems of

physics and technology can be solved, although in the light of our

present, insufficient knowledge it is by no means certain that they can.

One of the principal benefits of a study such as this is that it enables

these problems to be identified and defined.

The principal problem of plasma physics is the achievement of a

stable, high-β, closed-field plasma confinement system. The high-β is

essential if the reactor is to be kept small, and it is proposed to

achieve this in a highly elongated toroidal plasma. Present theories

say very little about highly elongated systems, but the experimental

results from the Garching Belt-Pinch are encouraging. Here $<\beta> = 0.6$

and the confinement is apparently classical,[24] although the temperature

is low ($T_e + T_i \sim 90$ eV). This interesting experiment is being

abandoned, apparently because no way can be seen, using conventional

electrical technology, to develop it into a fusion reactor. However,

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* When referred to the liner in its imploded state, a more impressive

number   is obtained, but it is not really relevant for comparison

with other systems.

the case is altered if electron beam technology is used to create the configuration and an imploding liner is used to compress it.

There are grounds for believing that the necessary imploding liner technology can be developed. Small scale experiments on hydrodynamic models have demonstrated rotational stabilization and reversible compression-expansion cycles.[3],[14] The main technical problem is to develop reliable mechanisms which can be scaled up to reactor size. One problem brought to light by the present study is the need to give the liquid metal a substantial amount of rotational energy as it enters the reactor, and to recover it upon leaving: the proposed pump-and-turbine arrangement would accomplish this, but is a rather cumbersome solution. The question is whether it is necessary to rotate the entire liner at the speed required for stabilization of its inner surface. The stability criterion simply requires that $\ddot{r} < r\omega^2$ at the surface. When the whole liner moves initially as a rigid rotor, Rayleigh's criterion $\frac{d}{dr}(r^2\omega)^2 \geq 0$ is satisfied everywhere and the fluid motion is completely stable. If only the inside layer were given the necessary rotation for surface stabilization, and the rest of the liner rotated more slowly, Rayleigh's criterion would not be satisfied, but, on the time scale of the implosion, the resulting internal instability might not grow sufficiently to affect the gross dynamics of the liner. In this case the main body of the liner would need to be rotated only at sufficient speed to establish a cylindrical surface ($\sim$ 25 rpm), and by injecting and extracting it with a tangential velocity component there would be no need to change the kinetic energy of a fluid element as it passed through the reactor. This question

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should be resolved by further calculations and hydrodynamic model experiments.

The two liquid metal circuits through the reactor are an unfortunate necessity, since the inner surface must be replaced between cycles and it is neither necessary nor desirable to replace the entire liner on this timescale. The arrangement would be considerably simplified if both circuits contained the same liquid metal. The choice of metals in the reference reactor was made in order to exploit the mechanical and nuclear properties of lead and the electrical and atomic properties of lithium, and no obvious combination of liquid metals can achieve the same result in a homogeneous liner. This does not rule out the possibility that a suitable combination might be found, but since there are so many properties which must be taken into account (e.g. density, sound speed, melting point, viscosity, electrical conductivity, nuclear cross-sections, vapor pressure, corrosiveness, etc.) the search may take some time.

The 22 MJ, 4.5 TW electron beam contains about seven times more energy than the largest existing electron beams produced by the Aurora generator[34] (3 MJ). Its power is only about one-fifth of Aurora's 24 TW on account of its much longer pulse length (5 μsec vs. 120 nsec). The beam could be produced by means of an annular field-emission diode connected to a 25 MJ Marx generator. Such a generator, operating at 1.7 Hz, is within the capabilities of existing technology, but it would be very large (~ 1000 m^3) owing to the intrinsically low energy storage density of capacitors. The same amount of energy could be stored in an inductor occupying only ~ 10 m^3, but to discharge an

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inductive store requires opening the circuit and there is as yet no switch, or combination of switches, capable of repetitively opening 1.5 MA against 3 MV. Light-activated silicon switches,[36] although at an early stage of development, may eventually fill this role, in which case the 22 MJ generator would probably be no larger than depicted in Fig. 11.

In conclusion, it appears that there is no fundamental obstacle to the development of the Linus reactor, although extensive development work is needed in several areas. If indeed the reactor could be made as compact as this study suggests, its power density would be greater than any other magnetically-confined fusion system. This could have an important effect on the economic position of fusion relative to the LMFBR.

XIV. Acknowledgments

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Table 1
Reactor Working Point

Liner Properties:

$$\rho = 9.9 \text{ gm.cm}^{-3}; \quad \rho c^2 = 405 \text{ kbar (Lead, } 20\,^a/_o \text{ Lithium)}$$

$$\eta = 21.5 + .026T \ \mu\Omega\text{-cm} \quad \text{(Lithium, T in °C)}$$

Driving Pressure: 2400 psi $(p/\rho c^2 = 4 \times 10^{-4})$

Plasma Conditions:

	Initial	Compressed
Radius	161 cm	13 cm
Length	12.9 m	12.9 m
Density	$8 \times 10^{14} \text{cm}^{-3}$	$2 \times 10^{17} \text{cm}^{-3}$
Temperature	376 eV	15 keV
Magnetic field	4.9 kG	506 kG
Pressure	1 bar	10 kbar $(p/\rho c^2 = 0.025)$
$<\beta^2>$	0.64	0.4
Energy (plasma + field)	11.1 MJ	864 MJ

Energies Per Cycle:

E-beam energy	22MJ
Final plasma energy	864 MJ
Nuclear energy (22.4 MeV/reaction)	1869 MJ $(Q_p = 2.16)$
Thermal energy	1891 MJ

Cycle Repetition Rate: 1.67 Hz

Power Accounting:

Gross thermal power	3165 MW
Gross electric power	1000 MW
Power to reactor motor, sodium circulators and BOP	60 MW
Power to e-beam generator	40 MW
Net electric power	900 MW
Plant net efficiency	28.4%

Table 2

Variation of Main Reactor Parameters with Driving Pressure

Driving pressure, psi:	1200	1800	2400	3000	3600	4200
Initial liner radius, m:	2.11	1.79	1.61	1.49	1.37	1.27
Length of liner, m:	16.8	14.3	12.9	11.9	10.9	10.1
Radial compression ratio:	13.5	12.8	12.5	12.3	11.2	10.3
Initial energy, MJ:	10.9	11.1	11.1	11.2	12.2	13.2
Nuclear energy per cycle, MJ:	2075	1930	1869	1855	1716	1602
Repetition rate, Hz:	1.51	1.62	1.67	1.69	1.82	1.94
Comparative weight factor:	1.02	0.95	1.00	1.05	1.04	1.03

Table 3

Basic Reactor Weights and Costs

Machine:

Main frame	645 tonnes @ $22K/tonne	=	$14M
Gas reservoirs	1230 tonnes @ $11K/tonne	=	14M
Rotor and mechanisms	535 tonnes @ $33K/tonne	=	18M
Ends and manifolds	900 tonnes @ $22K/tonne	=	20M
Liquid metal in reactor	500 tonnes @ $4K/tonne	=	2M
Sub totals	3810 tonnes		$68M

Electron beam generator:

22 MJ @ $1/J	200 tonnes (estimated)	$22M

Driving motor:

10,000 h.p.	70 tonnes	$2M
Totals	4080 tonnes	$92M

These costs are for the nuclear island only and do not include the
heat exchangers and the ancillary systems.

Table 4

Power Density and Materials Requirements

	Engineering Power Density (MW(t)/m^3 of metal)		Materials Requirements
	Energy Production Only	Total Nuclear Island	(Tonnes/ MW(e))
LMFBR*	350 (Core)	3	6
DT Fusion (Average)*	3-4 (Blanket)	1-2	15
Linus	80 (Liner)	6	4

* From Kulcinski[32]

(d) PLASMA EXPANDS.
HELIUM RE-COMPRESSED.

(c) PLASMA COMPRESSED.
FUSION OCCURS.

LINER

HELIUM

PLASMA

(a) LINER AT REST.
HELIUM STORED.
VALVES CLOSED.

(b) VALVES OPEN.
IMPLOSION BEGINS.
PLASMA FORMED.
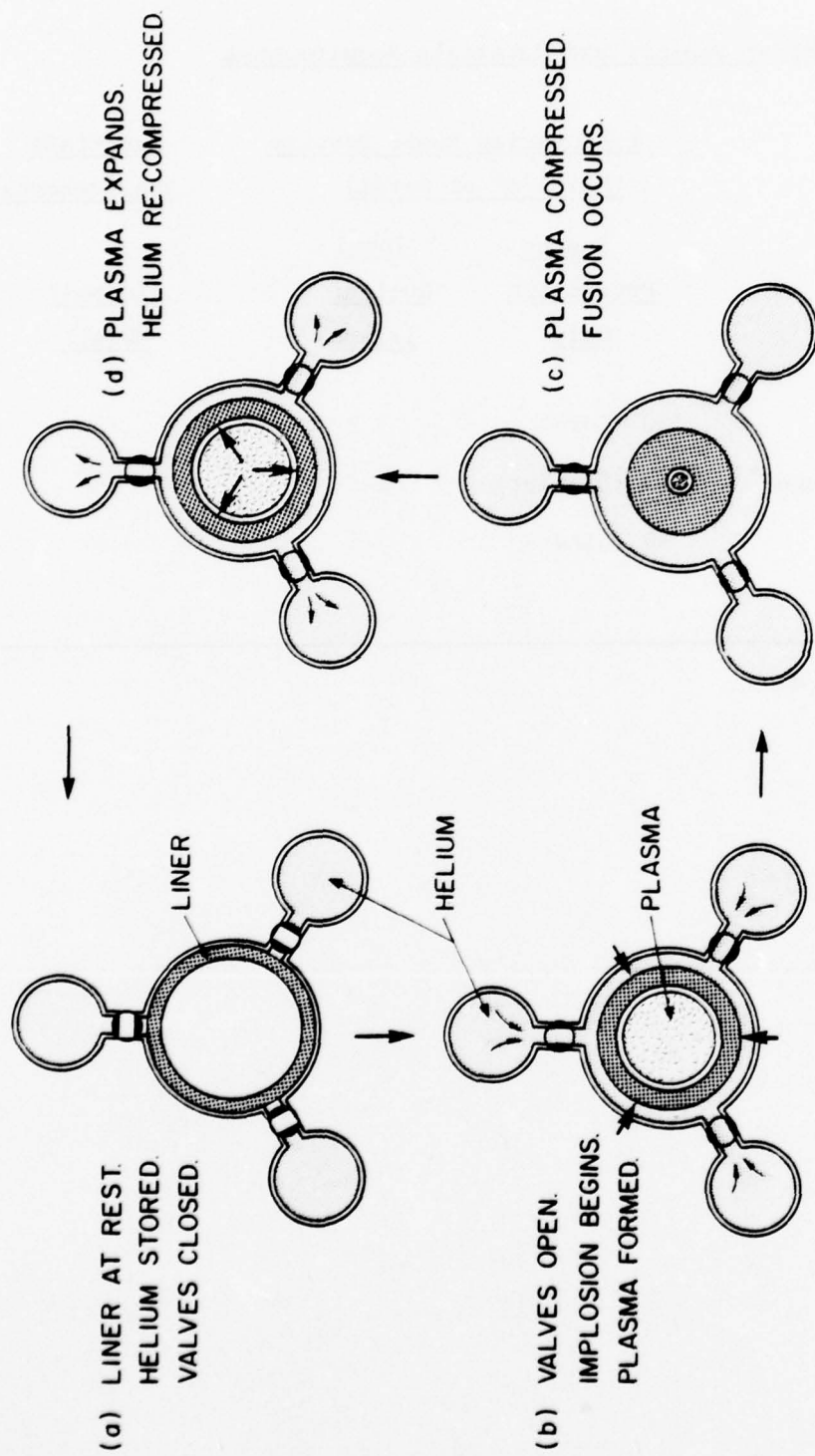
Fig. 1 — Linus reactor cycle

34
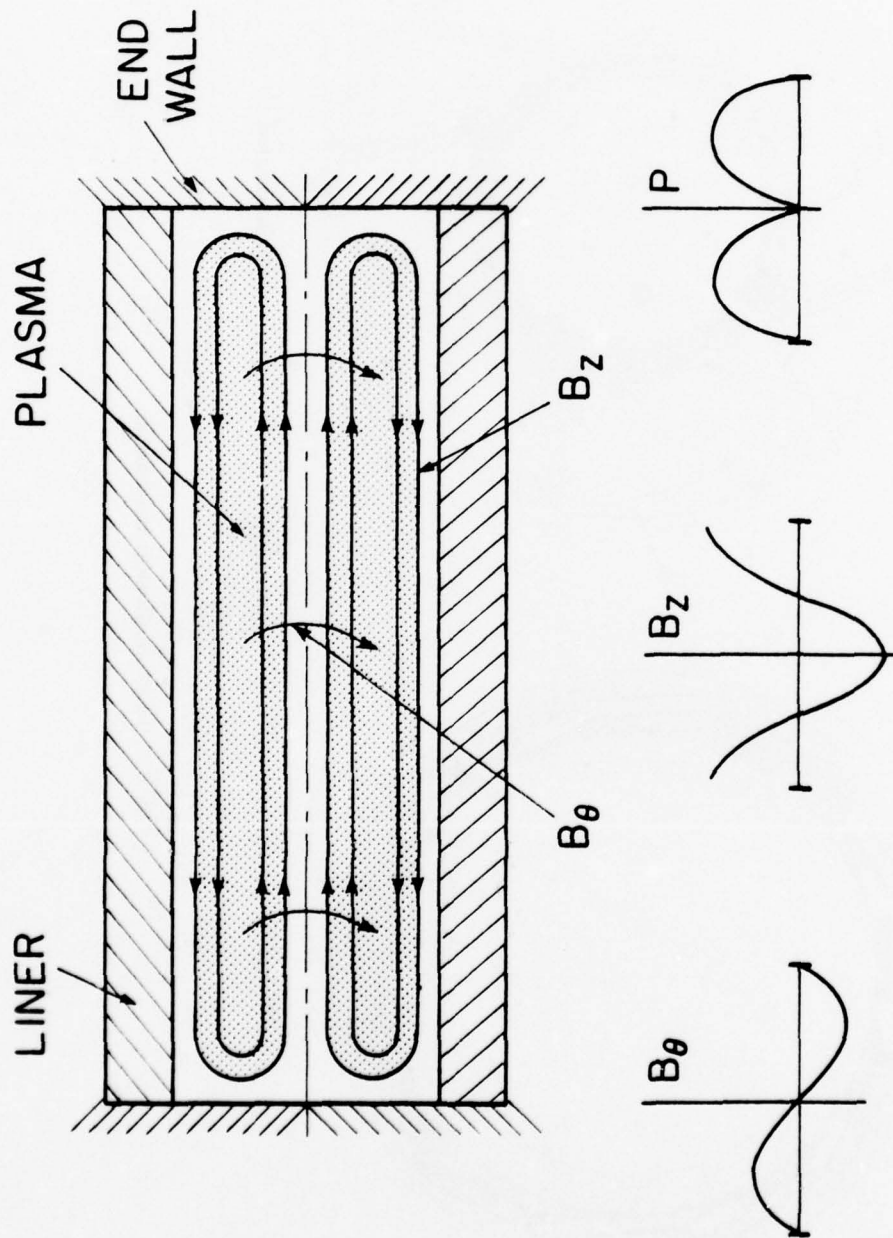
Fig. 2 — Closed-field plasma configuration inside liner
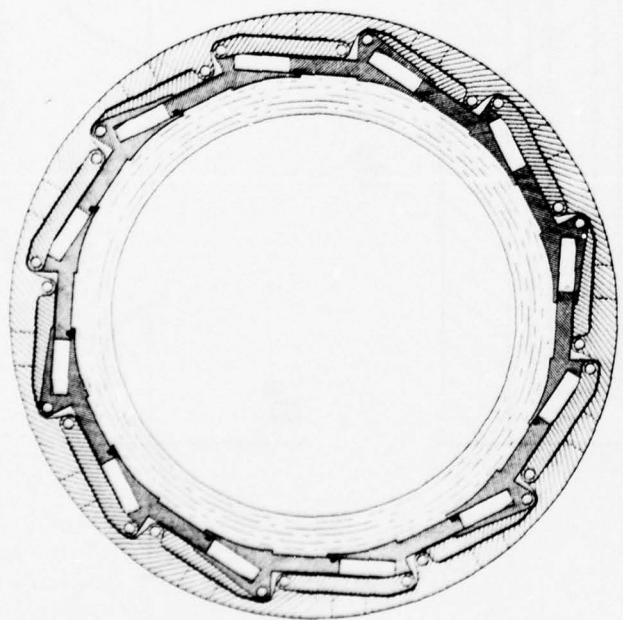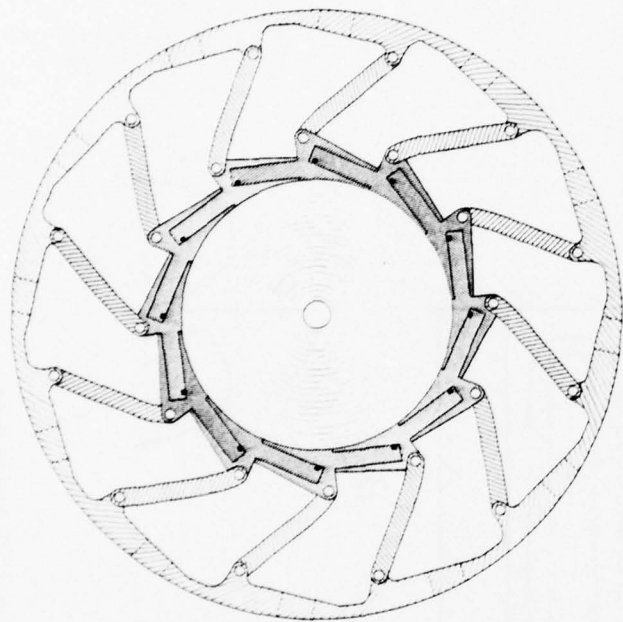
(a) open   (b) imploded

Fig. 3 — Liner implosion mechanism
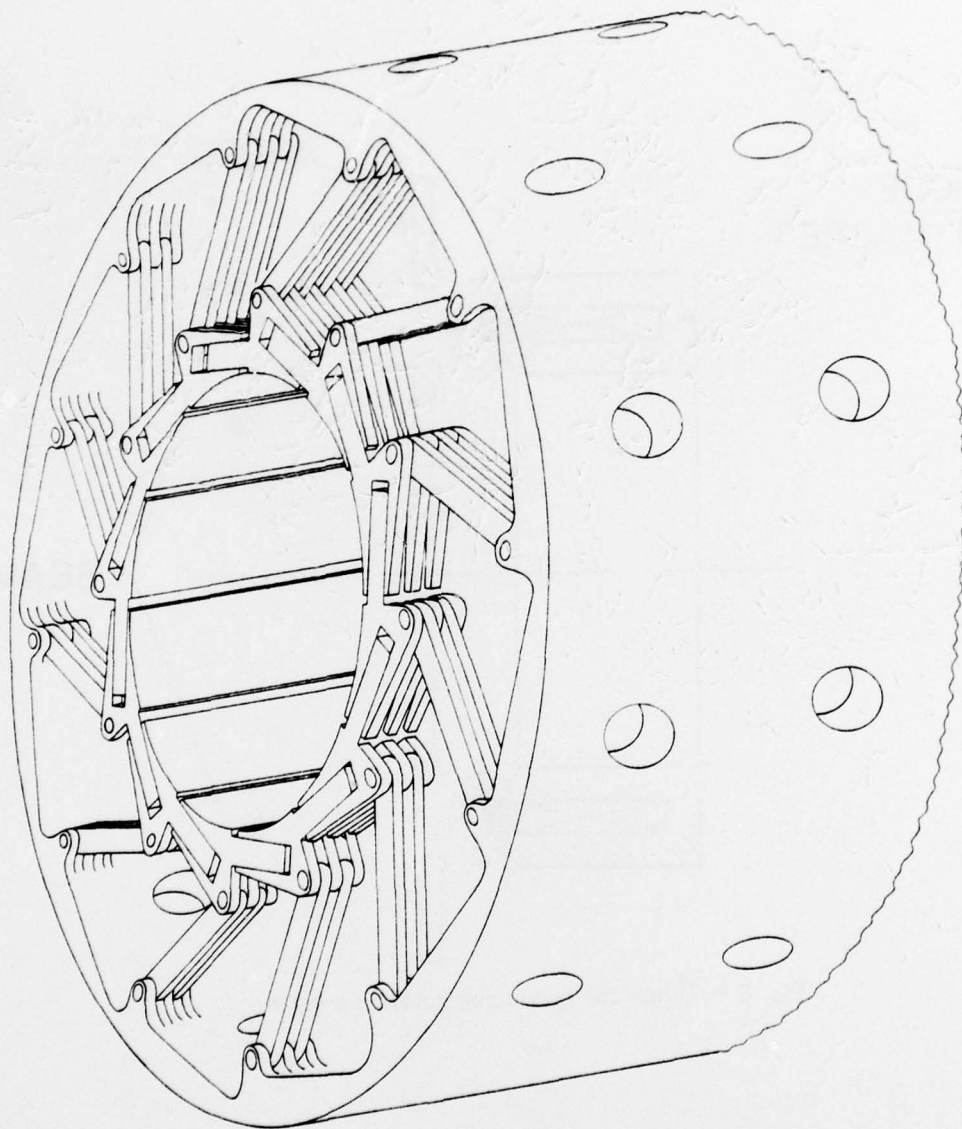
Fig. 4 — Liner implosion mechanism - 3D view

37
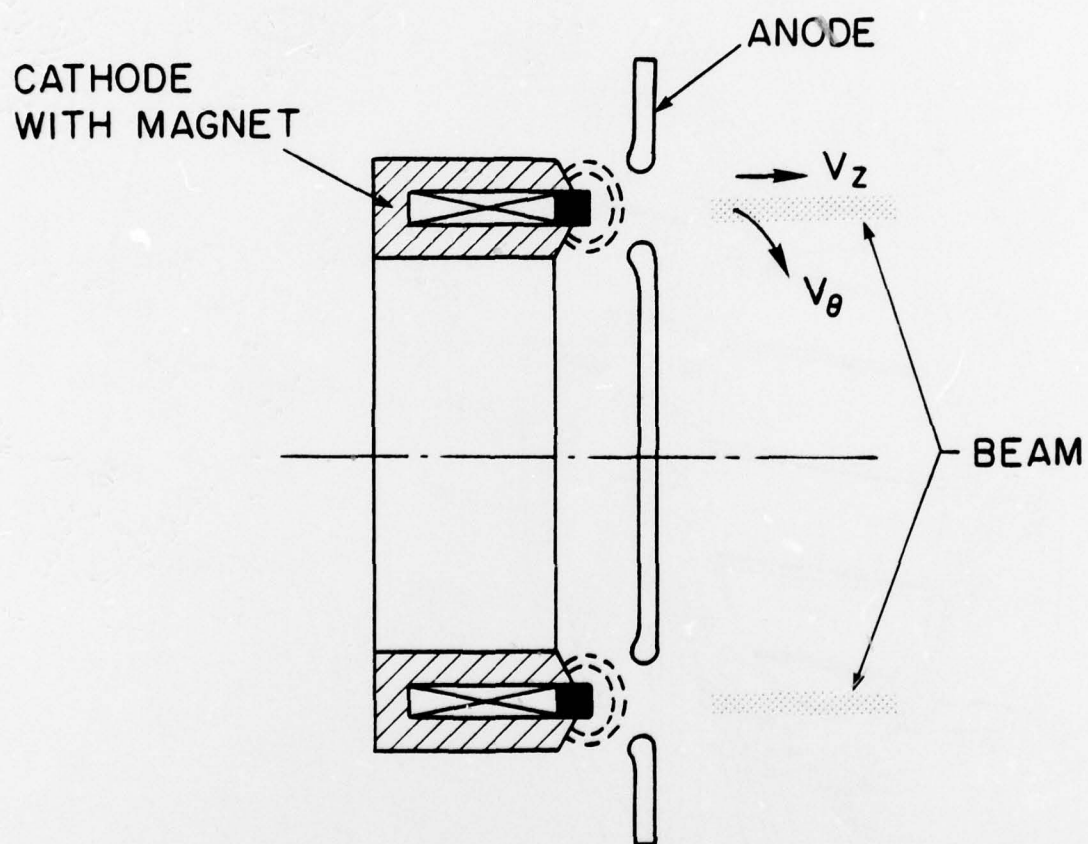
Fig. 5 — Diode for producing rotating e-beam

② PLASMA IS HEATED

④ PLASMA CURRENTS PERSIST

① BEAM ENTERS, BREAKS DOWN GAS

③ BEAM EXITS, INDUCING PLASMA CURRENTS
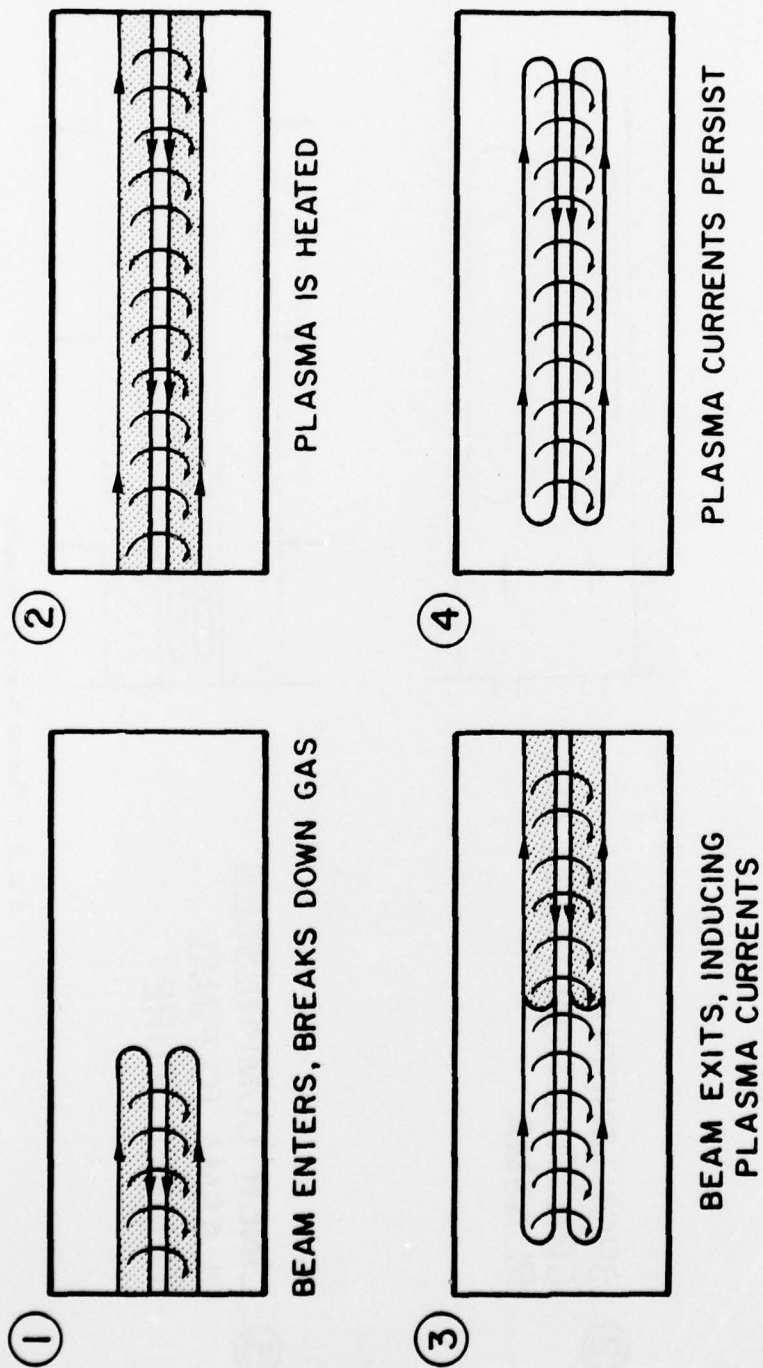
Fig. 6 — Formation of reversed-field plasma configuration by rotating relativistic electron beam

① ELONGATED PLASMA
FORMED BY E-BEAM
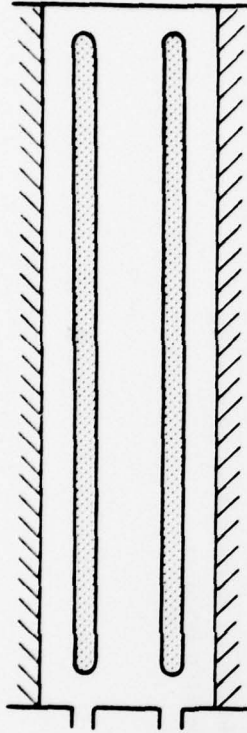
② SPONTANEOUS AXIAL
CONTRACTION PREHEATS
PLASMA
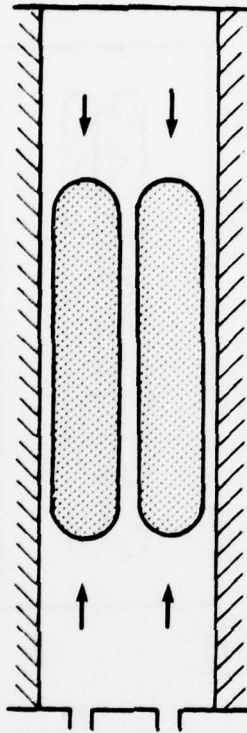
③ LINER COMPRESSES
PLASMA TO FINAL
TEMPERATURE
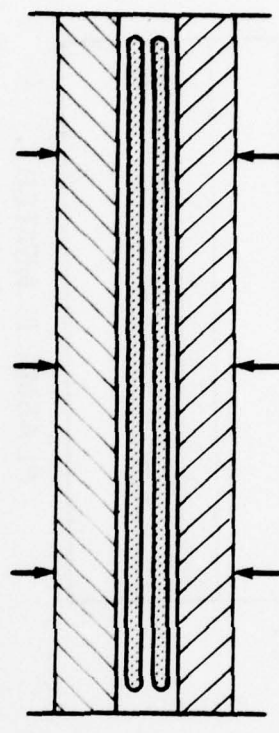
Fig. 7 — Plasma heating sequence

40

PUMP

LINER

TURBINE

HEAT EXCHANGER
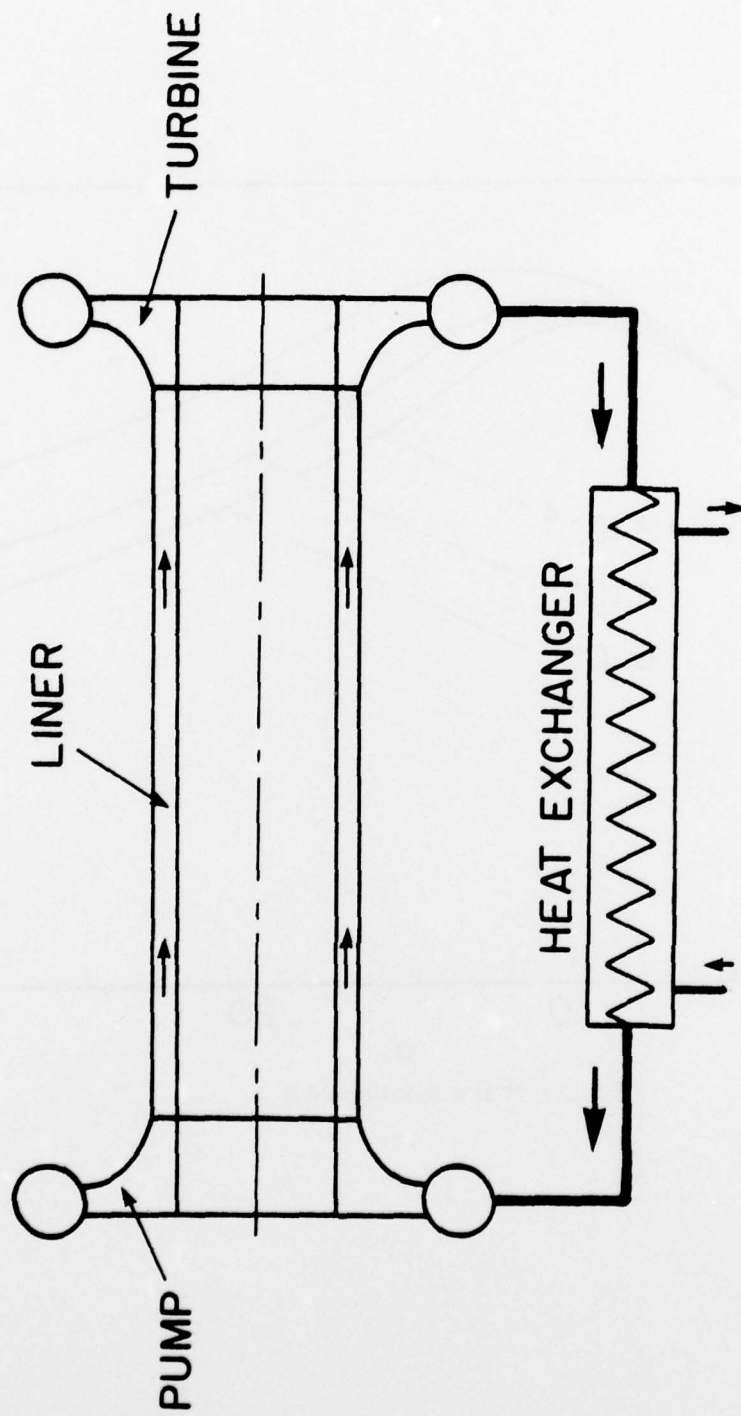
Fig. 8 — Liquid metal circuit

41
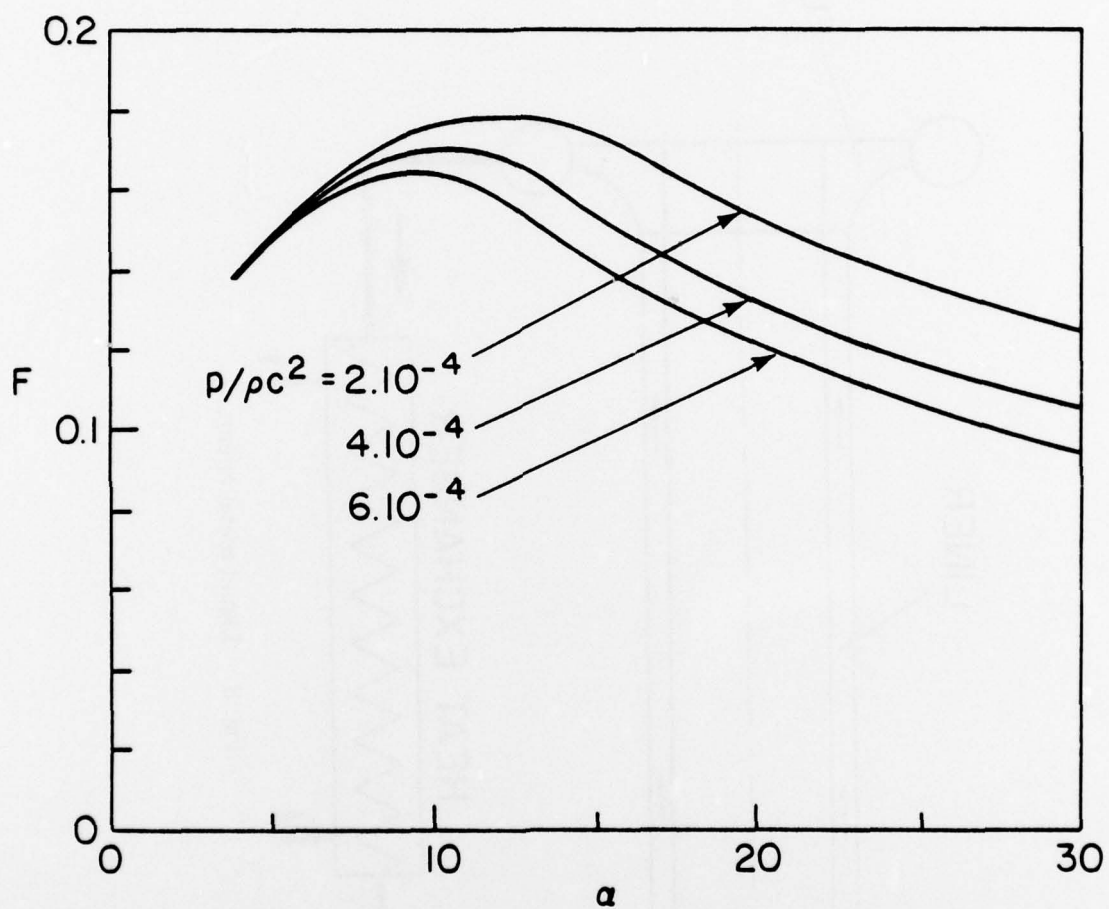
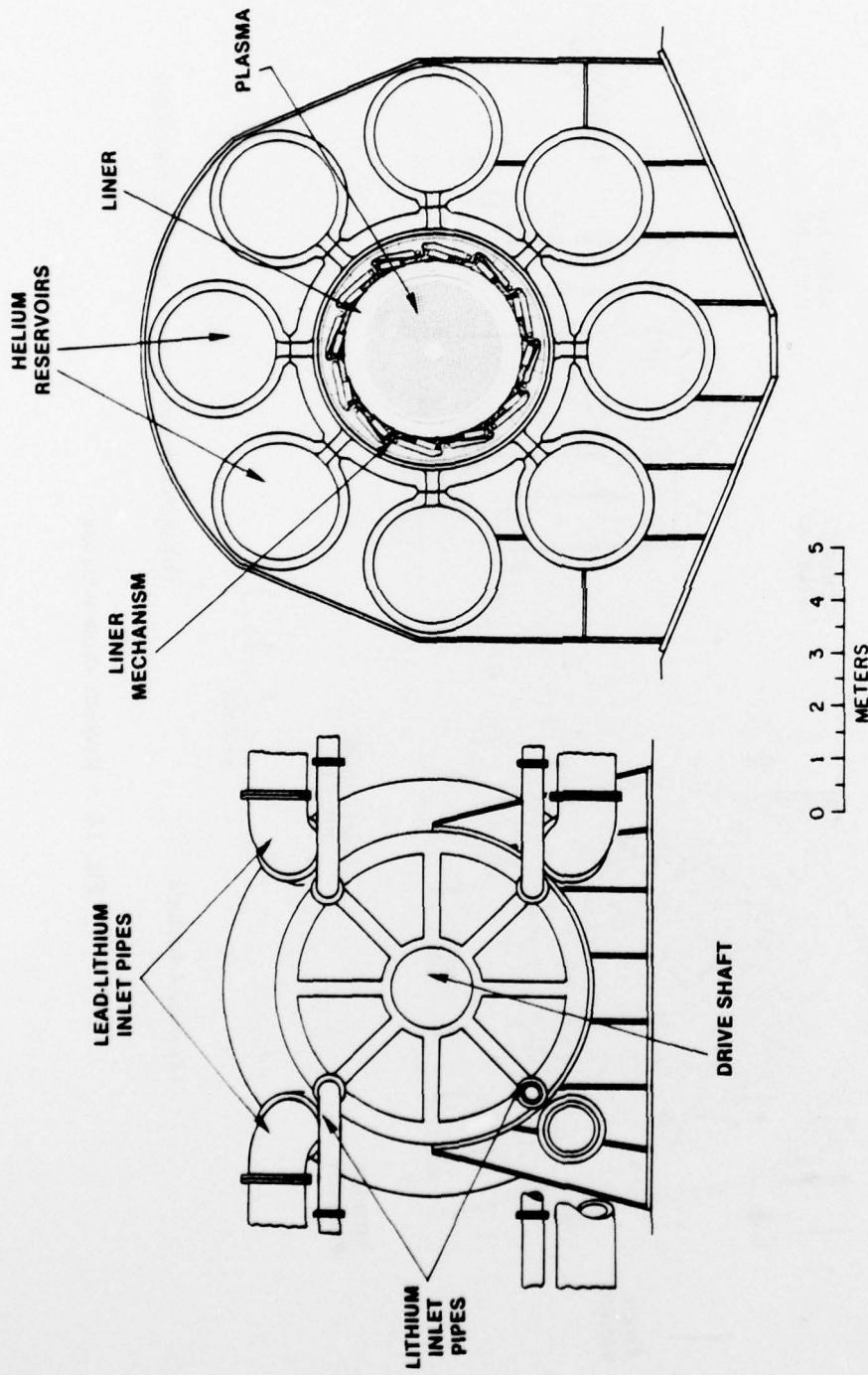Fig. 9 — F as a function of a

42

Fig. 10 — Liner implosion trajectory

43

LEAD-LITHIUM
TURBINE

LITHIUM
TURBINE

ELECTRON
BEAM
GENERATOR

SHUTTER

HELIUM
RESERVOIR

LINER

PLASMA

0 1 2 3 4 5
METERS

LEAD-LITHIUM
PUMP

LITHIUM
PUMP

MOTOR

LINER
MECHANISM

Fig. 11 — Reactor layout

44

PLASMA

LINER

HELIUM
RESERVOIRS

LINER
MECHANISM

LEAD-LITHIUM
INLET PIPES

LITHIUM
INLET
PIPES

DRIVE SHAFT

METERS

0 1 2 3 4 5
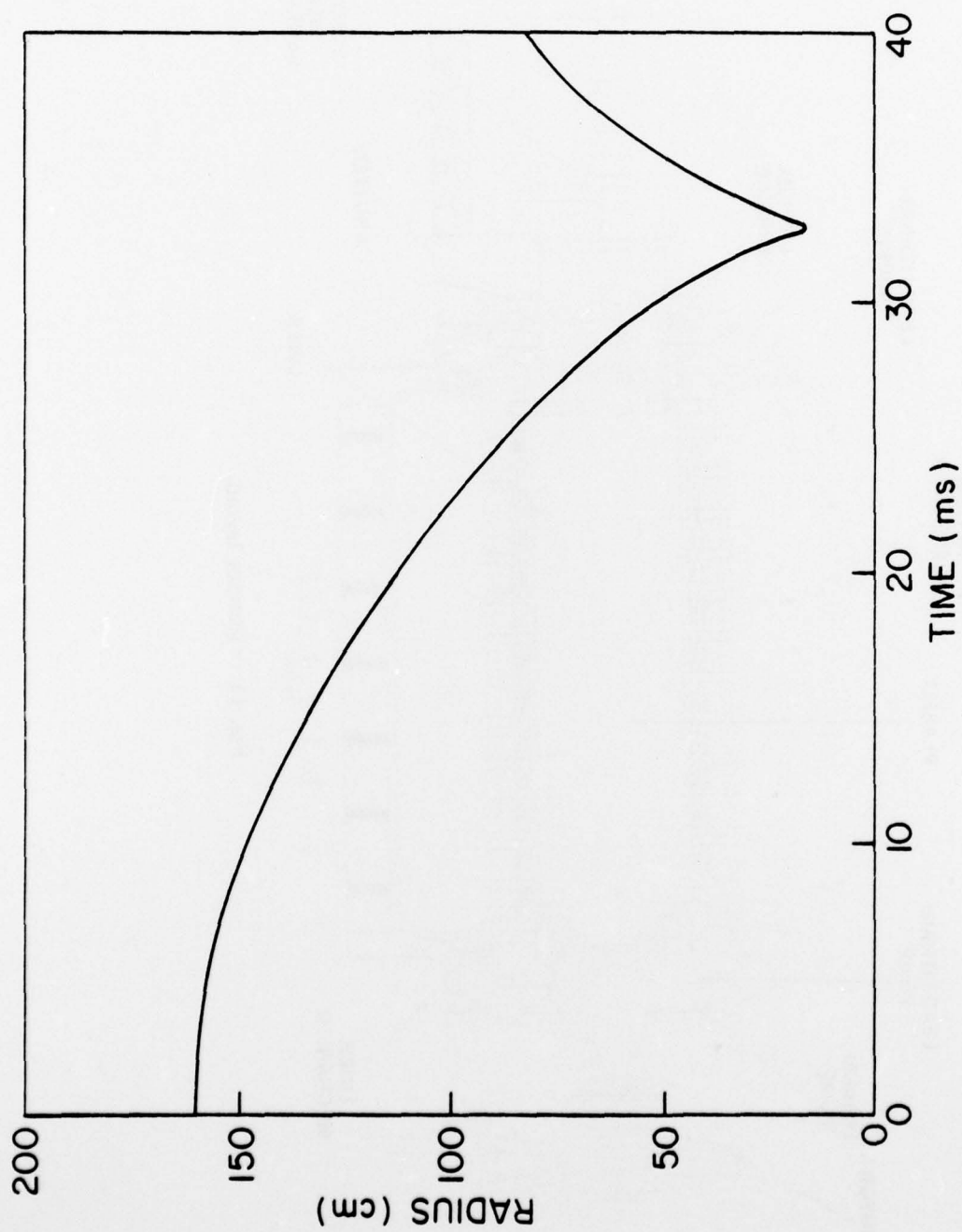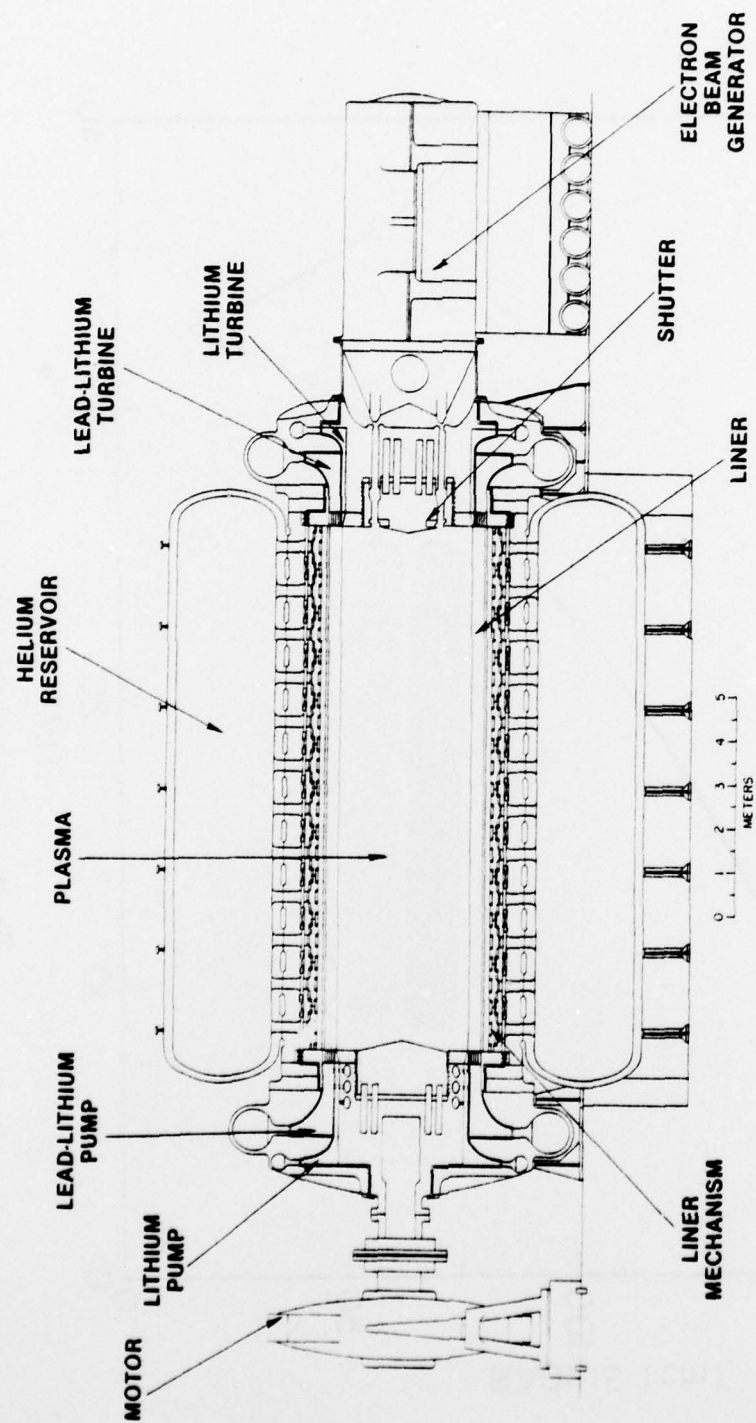
(a) end view and inlet manifold

(b) cross-section at mid-plane

Fig. 12 — Reactor layout

45

TURBO-MOLECULAR
PUMP

ANNULAR
CATHODE

ENERGY
STORAGE

ELECTRON BEAM
CHANNELS

LEAD-LITHIUM
TURBINE

LEAD-LITHIUM
OUTLET

LITHIUM
PASSAGE

FIXED
VANES

0 1 2 3 4 5
METERS

(a) outlet turbine   (b) injector and vacuum pumping manifold
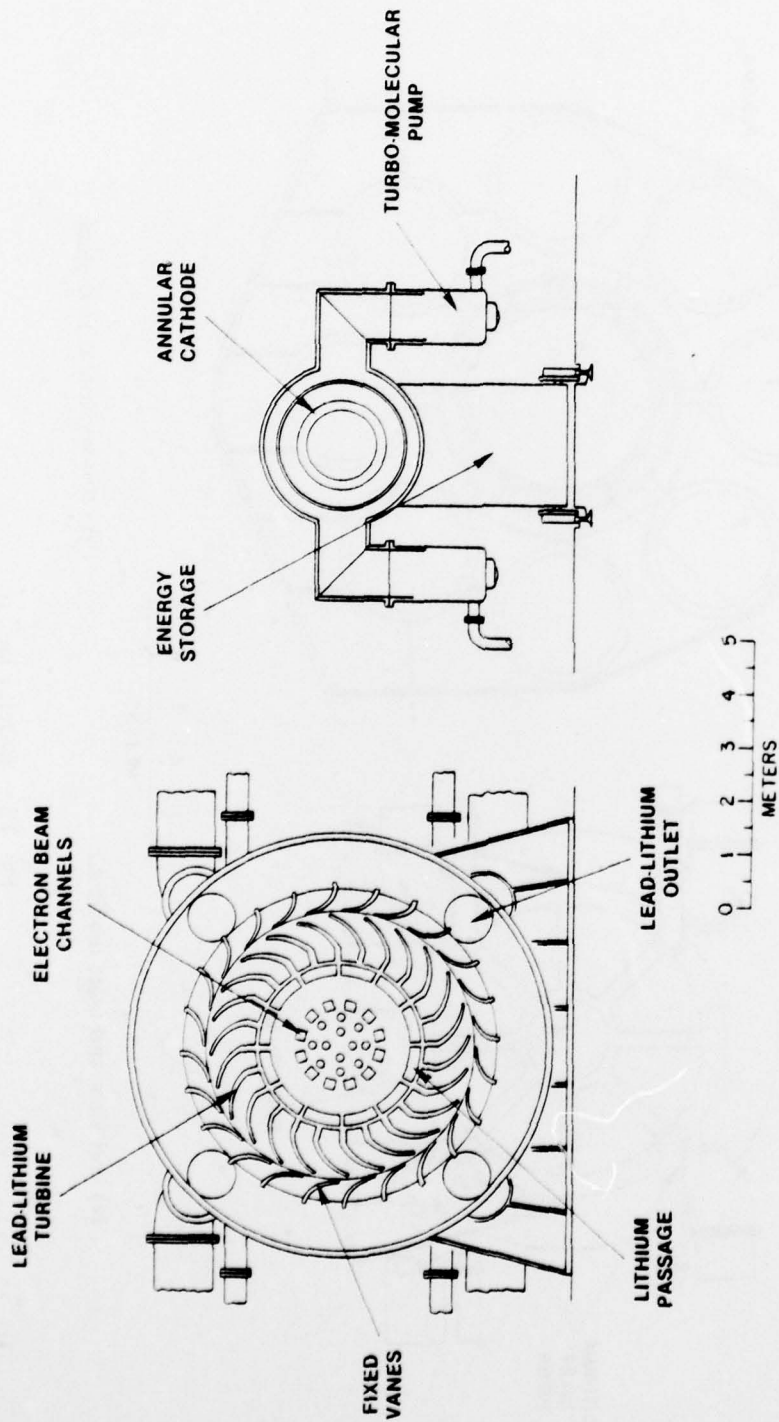
Fig. 13 — Reactor cross-sections

46

closed

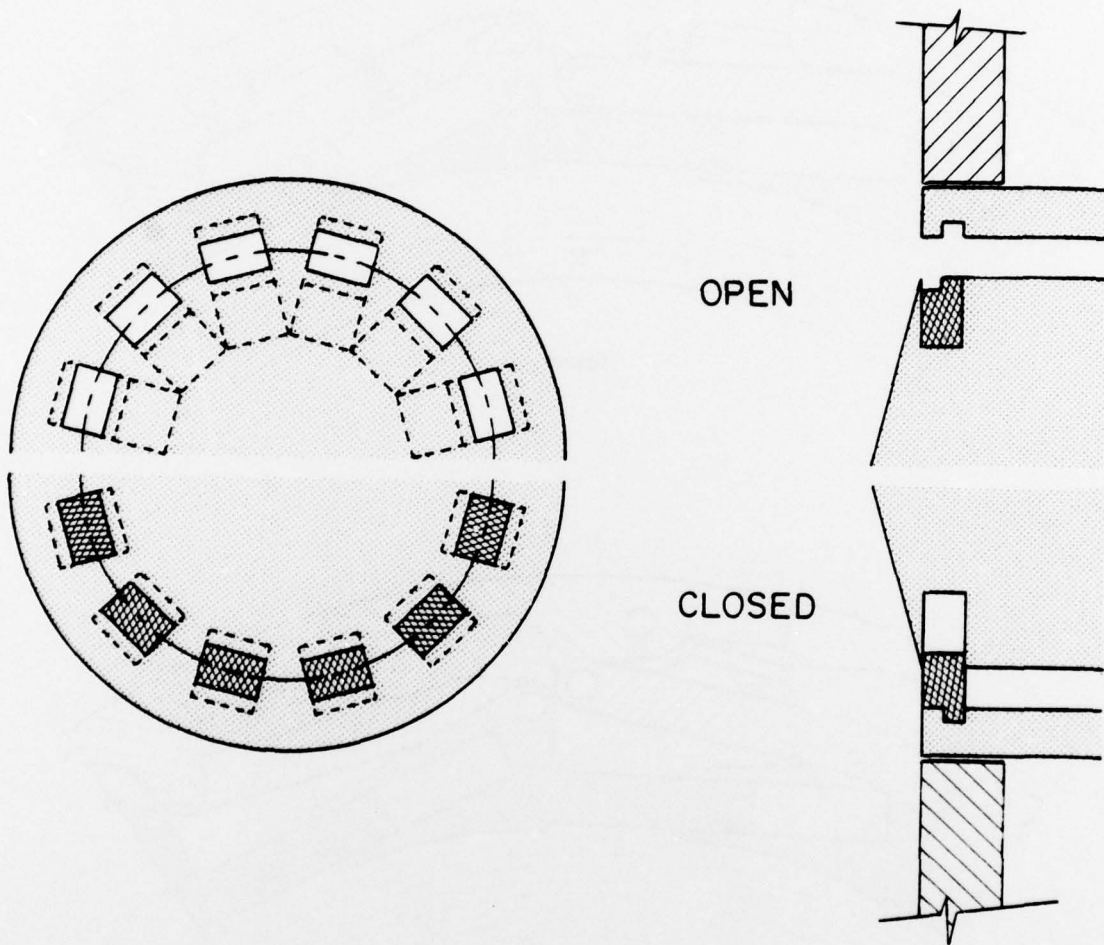activated
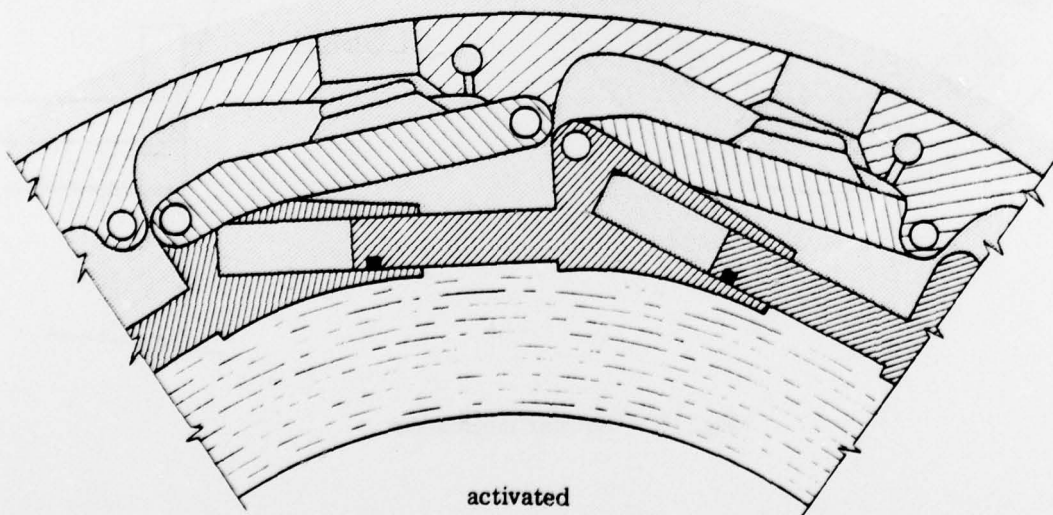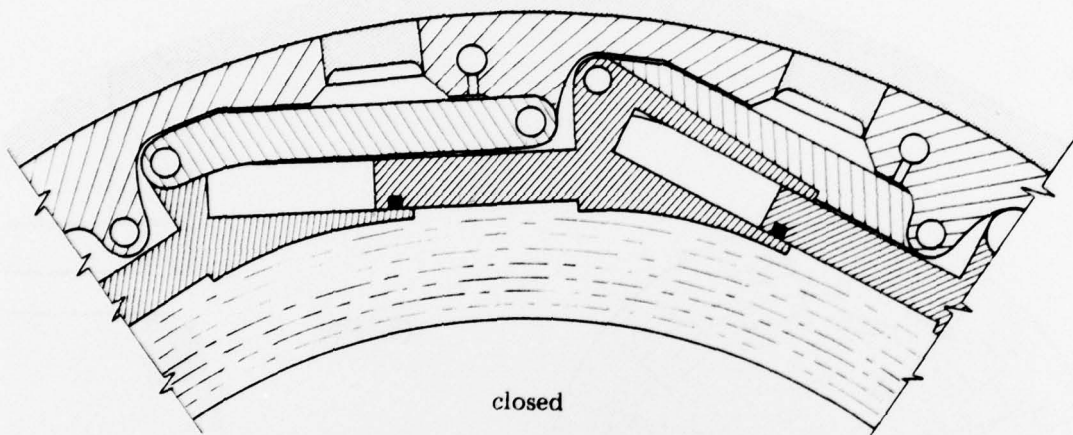
Fig. 14 — Valve mechanism
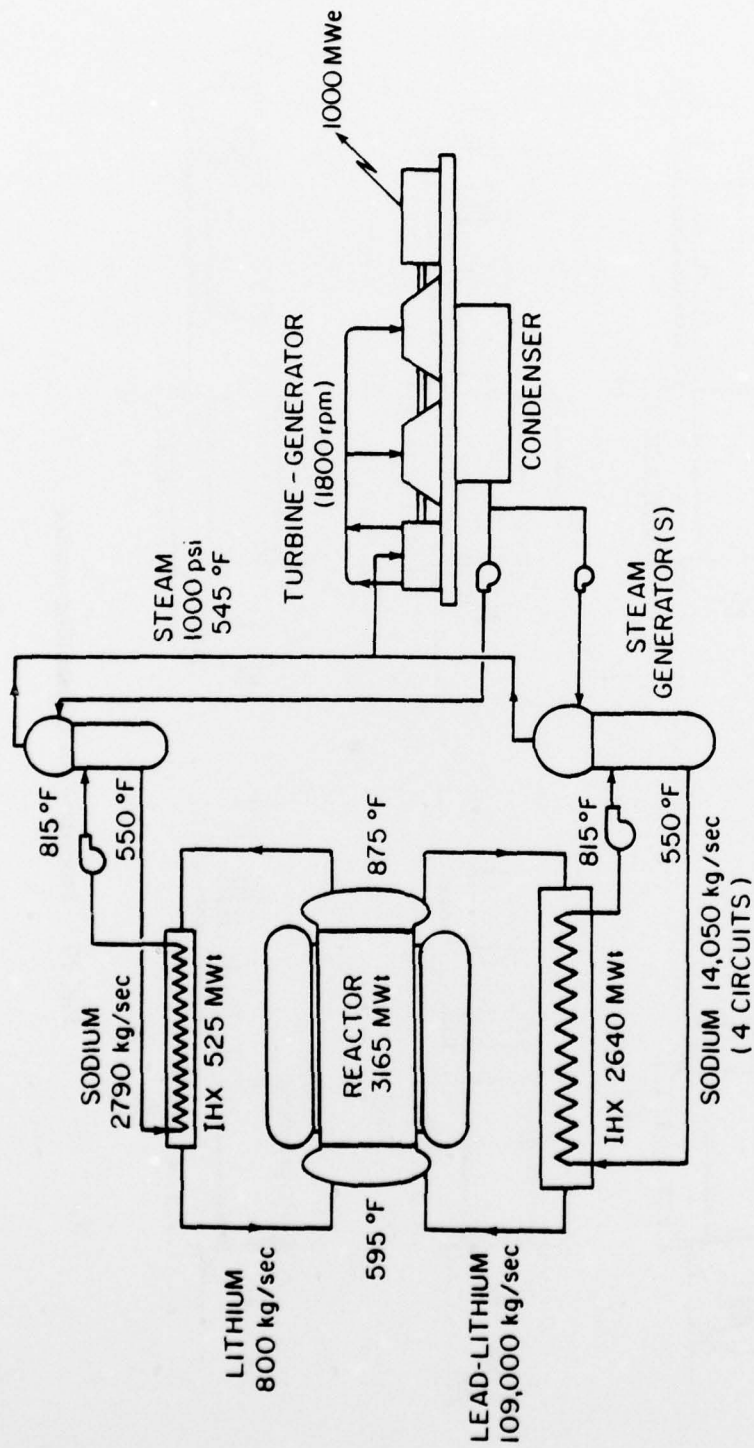
47

OPEN

CLOSED

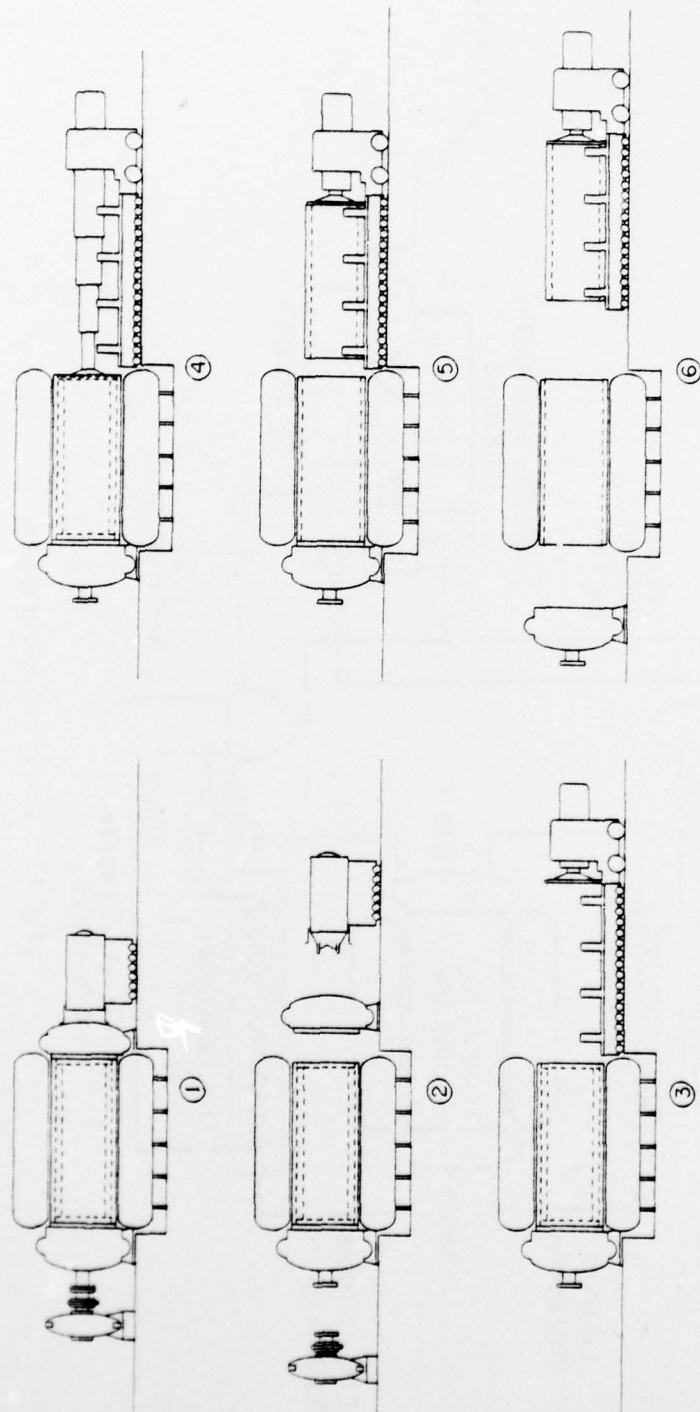Fig. 15 — Shutter mechanism

48

Fig. 16 — Energy conversion system

49

Fig. 17 — Procedure for dismantling reactor

50